

Extragalactic Jets: Theory and Observation from Radio to Gamma Ray
ASP Conference Series, Vol. N/A, 2007
T. A. Rector and D. S. De Young (eds.)

X-ray Observables of Magnetically Dominated Cavities in Clusters

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Abstract. We present results from magneto-hydrodynamic jet simulations in the magnetically dominated regime and find that they inflate cavities into the intracluster medium. Mock *Chandra* X-ray observations of our simulations show a strong resemblance to real cavities observed in X-ray images of clusters, both in terms of their morphology and thermodynamic structure. An analysis of the evolution of bubble sizes in the multi-cavity system Hydra A, as well as in a large sample of 64 cavities in 32 clusters shows that bubbles tend to expand much faster than expected in the purely adiabatic regime. Instead, we find that the bubbles follow more closely a trend predicted by our current-carrying jet models.

1. Introduction

The cooling time of the hot gas in the center of clusters is significantly shorter than the age of the cluster. Thus, the gas should have already cooled completely, dropped out of the X-ray phase and formed stars. This so-called cooling flow problem suggests that something is heating the gas, and effectively preventing it from cooling. Chandra observations of clusters reveal common features in the X-ray emission that point toward the central AGN to have a significant impact. Images often show deficits in the X-ray emission - generally referred to as cavities or bubbles - that are very often nicely filled with extended radio emission (see Bîrzan et al. 2004, and references therein).

So far, theoretical models of AGN feedback have focused on simulating purely hydrodynamic, kinematically supported jets. However, these simulations have so far failed to reproduce the observed X-ray morphology as depressions with enhanced rim emission and the thermodynamic structure of the bubbles, which often appear cooler in projection. In fact, bubbles in hydro simulations are very quickly shredded apart by Rayleigh-Taylor instabilities on the top and Kelvin-Helmholtz instabilities on the sides. Several ideas have been put forward to prevent this from happening, with two mechanisms showing the most promise: viscosity and magnetic fields. Our work focuses on the second idea, in particular the extreme case of magnetically dominated bubbles.

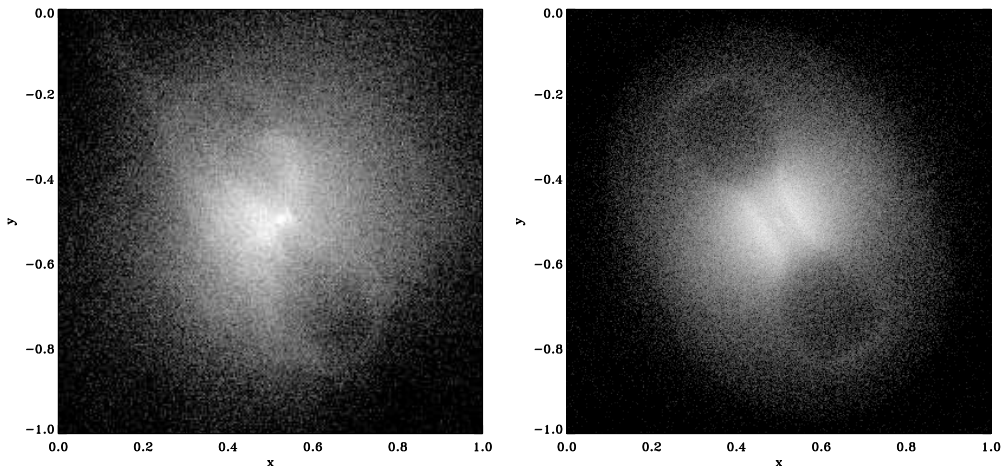


Figure 1. Qualitative morphological comparison between an actual *Chandra* observation and a mock *Chandra* image from our simulation. Left: X-ray image of the core of *Hydra A*; Right: Mock image of a simulated current-dominated MHD jet. Note the morphological similarities of depressed X-ray surface brightness at the location of the jet lobe, surrounded by enhanced rim emission. We emphasize that the rather wide width of the jet structure in the center is solely due to limited numerical resolution in this simulation.

2. Mock *Chandra* Observations from Magnetically Dominated Jet Simulations

We expand our earlier work on the first MHD simulations of magnetically dominated jets (Li et al. 2006; Nakamura et al. 2006, 2007). Our model only relies on the injection of non-force-free magnetic fields in the center of the cluster. These fields then expand and launch a magnetic tower. While doing so, the fields first self-collimate to form a current-carrying jet structure. When the ambient gas pressure starts dropping outside the X-ray core radius, the jet column then expands, forming the lobe. During the subsonic lobe inflation process, the lobe pushes the hot gas outward, and evacuates a cavity into the cluster atmosphere.

We then produce mock *Chandra* X-ray observations with the simulation tool MARX. Figure 1b shows X-ray snapshots of the evolution of one simulations with 200,000 counts. Note the depressed X-ray emission at the the location of the lobe, surrounded by enhanced rim emission. The magnetic fields successfully stabilize the bubbles against disruption. These key morphological features are very close to actual cluster observations, shown for Hydra A in Figure 1a. In projection the slow, subsonic expansion of the bubbles lets them actually appear cooler than their surroundings. To our knowledge, no purely hydrodynamic jet simulation has yet been able to reproduce this observational fact.

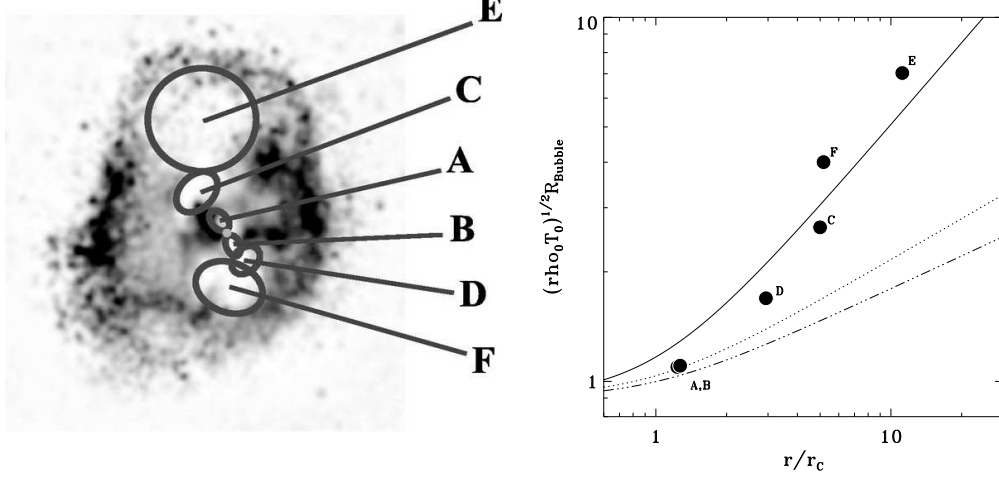


Figure 2. Left: Black colors show X-ray excess in *Chandra*'s *Hydra A* image, when an elliptical model is subtracted; circles demonstrate the location of cavities A-F (Figure reproduced from Wise et al. 2006, with permission from the authors); Right: Bubble size R_b as a function of bubble location r for the cavities A-F. The lines show several model predictions. Triple-dot-dashed line: purely adiabatic expansion for a $\Gamma = 5/3$; dotted line: same, but for $\Gamma = 4/3$; solid line: magnetically dominated, current-carrying jet (our model). Note that the evolution of the bubble sizes can be explained by a single current running through the system, whereas the adiabatic expansion model would require subsequently stronger outbursts. This figure has been reproduced from Diehl et al. (2007).

3. X-ray Cavity Sizes: Confronting Theory with Observations

3.1. Model Predictions: Adiabatic vs. Current Dominated

Purely hydrodynamic bubble models predict a very simple behavior as they rise adiabatically in the intracluster medium (assumed to follow an isothermal β -model). Thus, – assuming the bubble stays intact – keeping $pV^\Gamma = \text{constant}$ gives a prediction of the bubble size as a function of radius r :

$$R_{b,\Gamma} = R_{b,0} \left[1 + (r/r_c)^2 \right]^{\frac{\beta}{2\Gamma}}, \quad (1)$$

where $R_{b,0}$ denotes the fiducial bubble size projected back to the cluster center.

For our current-carrying MHD simulations we get a very different prediction. As the lobes are magnetically dominated, the size of the cavity is determined by the point where the external gas pressure balances the internal magnetic pressure ($\propto B^2$). This B-field is mainly generated by the current I_z , and falls off as I_z/R (Ampres law), thus predicting:

$$R_{b,I_z} = R_{b,0} \left[1 + (r/r_c)^2 \right]^{\frac{3\beta}{4}} \quad (2)$$

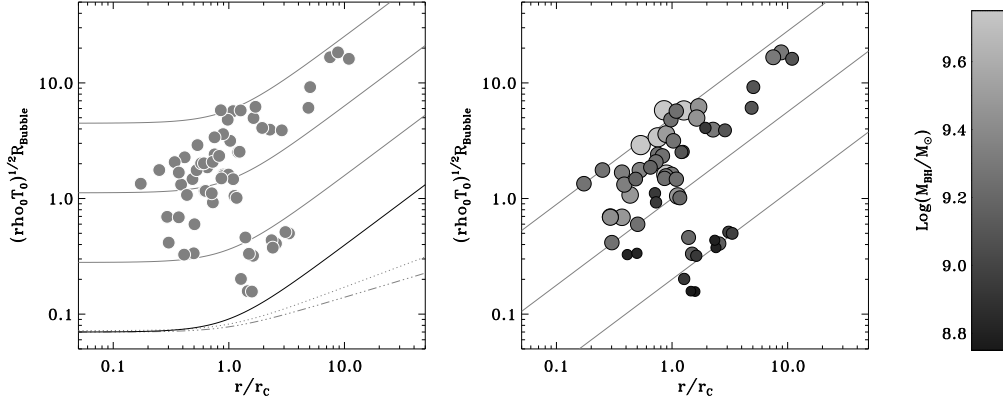


Figure 3. Left: Scaled bubble size R_b as a function of bubble location r for a sample of 64 cavities. The lines are the same as in Figure 2b; Right: Same plot, but now symbols are colored according to their black hole masses. Larger symbols with lighter color indicate larger black hole masses. This figure has been reproduced from Diehl et al. (2007).

In this magnetically dominated case, the bubble size $R_{b,0}$ projected back to the center is proportional to the current I_z that is being driven through the system.

3.2. A Perfect Test Case: The Multi-Cavity System *Hydra A*

Unfortunately, we cannot observe the same cavity multiple times as it rises in the cluster. However, cavities in the X-ray emission of clusters provide a unique fossil long-term record of past AGN activity. The multiple cavity system of Hydra A is a great example (Figure 2a), consisting of 3 pairs of bubbles at various radii. Assuming that each cavity pair was created by a similar outburst, we can then apply our formalism and test the predictions of the models. Figure 2b shows the radial evolution of the appropriately scaled bubble sizes (circles). The red lines show the predictions for the adiabatic bubbles (for $\Gamma = 4/3$ and $\Gamma = 5/3$), which severely underestimates the bubble sizes at large radii. However, the prediction from the magnetically dominated bubbles, denoted by the green line, fits the data very well. In order to explain the large bubble sizes at large radii with purely hydrodynamic models, one has to invoke successively larger outbursts or continuous inflation.

3.3. Statistical Approach: A Large Cavity Sample

Figure 3 shows the same plot of scaled bubble size vs. radius for a much larger sample of 64 cavities. Note that we observe the same radial trend as for Hydra A. Cavities at larger radii are overly large compared to predictions from purely adiabatic bubbles. However, the trend nicely follows the general slope expected for our magnetically dominated model. It is also worth noting that this result is independent of adding viscosity to the adiabatic model, as viscosity cannot magically inflate the bubble. The grey lines denote lines of constant current, spaced by factors of 4, indicating that the width of the correlation can be repro-

duced by a narrow range in currents (about a factor of 30). Figure 3b shows the same plot but with symbol sizes indicating the central BH mass. We find that more massive BHs drive larger currents and inflate bigger cavities.

While this result is suggestive, one has to keep one caveat in mind, namely incompleteness. Enßlin & Heinz (2002) have tackled this problem by analytically computing the signal-to-noise ratio of a spherical void in a single-temperature β -model atmosphere. As we do not have an automatic bubble detection tool, but rather identify cavities manually by eye, it is difficult to estimate how incompleteness really affects our sample. Nevertheless, we can definitely say that magnetically dominated cavities will be much easier to identify, as they stay intact and expand much faster in general. To put a quantitative constraint on the nature of bubbles in cluster atmosphere, we need Monte-Carlo simulations of bubbles including incompleteness effects, which are currently underway and will be presented in a forthcoming paper (Diehl et al. 2007).

4. Conclusions

We present results from magnetically dominated, current-carrying jet structures in clusters, and show that these jets subsonically inflate bubbles into the intracluster medium. We find that the helical magnetic field lines support these bubbles and stabilize them against Rayleigh-Taylor and Kelvin-Helmholtz instabilities.

Mock Chandra observations show that the inflated bubbles morphologically and thermodynamically strongly resemble the cavities found in X-ray observations of clusters. In particular, we find enhanced rim emission surrounding the cavities, as well as an effective decrease in temperature at the bubble location.

An analysis of bubble sizes in the multiple cavity system Hydra A, as well as in a large sample of 64 cavities in 31 clusters favors magnetically dominated cavities over purely hydrodynamic bubbles. An analysis of incompleteness effects will be addressed in an upcoming paper (Diehl et al. 2007).

Based on the assumption that our model is correct, we find that the current flowing in these systems depends on the central BH mass, offering a potential way to constrain BH mass from imaging X-ray observations.

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